[0120] As described above, the thin-film structure **40** having a certain thickness or greater may be deposited on the oxide substrate **20** within a short period of time, by forming the thin-film structure **40** on the oxide substrate **20** by using a pulsed laser deposition method. For example, the thin-film structure **40** having a thickness ranging from about 10 nm to about 100 nm may be formed on the oxide substrate **20** within two hours.

Example Embodiment

[0121] A mixture may be prepared by mixing raw metal materials including one or more of Bi, Sb, and Te with each other in correspondence with a composition ratio therebetween, so as to obtain a thermoelectric material having a composition equation of $Bi_{0.5}Sb_{1.5}Te_3$. The prepared mixture may be put into a quartz tube and sealed, and then, melted at a temperature of about 1000° C. for 10 hours. Then, the prepared mixture is maintained at a temperature of about 650° C. for two hours, and then, the temperature is reduced by using water at a room temperature. Thus, a thermoelectric structure of $Bi_{0.5}Sb_{1.5}Te_3$ in an ingot form may be manufactured.

[0122] After 10 g of the thermoelectric material in the ingot form is manufactured, the thermoelectric material is evenly ground at about 1425 rpm for two minutes by using a high-energy ball mill, and thus, a powder of the thermoelectric material is manufactured.

[0123] The target T for thin-film deposition is manufactured by sintering the powder at a temperature of about 480° C. for two minutes under a pressure of about 70 Mpa in a vacuum state by using a spark plasma sintering method.

[0124] The laser light L may be applied to the manufactured target T by using a pulsed laser deposition method, and thus, $Bi_{0.5}Sb_{1.5}Te_3$ is deposited on the Al2O3 oxide substrate **20** in the form of a thin film for about 1.5 hours.

[0125] FIG. **5** illustrates an image obtained by observing the manufactured thermoelectric structure **10** by using an optical electronic microscope, according to some example embodiments. FIG. **6** is a graph showing a result of measuring a chemical component in a direction of a thickness of the thermoelectric structure **10** according to an energy dispersive X-ray (EDX) analysis.

[0126] Referring to FIG. **5** and FIG. **6**, it may be determined that the buffer layer **30** that includes tellurium oxide (TeOx, where x is a positive number) is formed between the Al2O3 oxide substrate **20** and the thin-film structure **40** that is formed of

[0127] $Bi_{0.5}Sb_{1.5}Te_3$.

[0128] Referring to FIG. **6**, it may be understood that the buffer layer **30** containing Te and O is formed between the oxide substrate **20** containing aluminum (Al) and O and the thin-film structure **40** containing Bi, Sb, and Te. The buffer layer **30** has a thickness of about 1.6 nm.

[0129] Characteristics of the thin-film structure **40**, formed on the buffer layer **30**, may be measured and/or observed. The characteristics of the thin-film structure **40** are described with reference to FIG. **7**A, FIG. **7**B, FIG. **7**C, FIG. **8**A, FIG. **8**B, FIG. **9**, and FIG. **10**.

[0130] FIG. **7**A, FIG. **7**B, and FIG. **7**C are graphs showing results of two-theta (2θ) scanning, omega (Ω) scanning, and phi (ϕ) scanning of the thin-film structure **40**, respectively. FIG. **8**A illustrates a conceptual diagram of a measuring apparatus for measuring heat conductivity of the thin-film structure **40**. FIG. **8**B is a photograph of the measuring apparatus shown in FIG. **8**A, taken in a downward direction from above. FIG. **9** is a graph showing a state of the measuring apparatus shown in FIG. **8**A. FIG. **10** is a graph showing heat conductivity of the thin-film structure according to some example embodiments.

[0131] Referring to FIG. **7**A, FIG. **7**B, and FIG. **7**C, occurrence of a peak with a certain interval may be observed from a result obtained by 2θ-scanning the thin-film structure **40**. Thus, it may be understood that the plurality of thin-film layers **41** are formed to have a same thickness. Additionally, an FWHM obtained by w-scanning the thin-film structure **40** is 0.083 degrees. Thus, it may be understood that crystallization of the thin-film structure **40** is enhanced.

[0132] Referring to FIG. **8**A and FIG. **8**B, a metal thin-film **210** formed of gold (Au) and electrodes **221** and **222** formed of silver (Ag) are disposed on the thermoelectric structure **10**. In such a structure, heat may be periodically applied to the metal thin film **210** so as to measure heat conductivity (K) of the thin-film structure **40**.

[0133] The measuring apparatus may measure the heat conductivity (K) of the thin-film structure **40** over a range of electrical conductivity as shown in FIG. **9**. In other words, the measuring apparatus measures the heat conductivity (K) of the thin-film structure **40** when the measuring apparatus is stable.

[0134] Referring to FIG, **10**, with respect to **200** or more thin-film structures **40** manufactured by using the method described above, heat conductivity thereof in a direction of a c-axis is measured. The heat conductivity, obtained as a result of the measuring, is about 0.18 W/(m·K) to about 0.22 W/(m·K). A thickness of the **200** or more thin-film structure **40** is about 30 nm.

[0135] Unlike the example, in a comparative example, if a thin-film structure is formed on an oxide substrate and does not include the buffer layer **30** that includes tellurium oxide, when a thickness of the thin-film structure is 5 nm, heat conductivity of the thin-film structure in a c-axis is about 0.49 W/(m·K), and heat conductivity of the thin-film structure in an a-b axis is about 0.97 W/(m·K).

[0136] The heat conductivity of the thin-film structure in the a-b axis may be greater than the heat conductivity of the thin-film structure in the c-axis. Accordingly, if a thickness is increased, the heat conductivity of the thin-film structure in the c-axis is affected by the heat conductivity of the thin-film structure in the a-b axis, and thus, increased. However, it may be understood that the thin-film structure **40** in the example embodiment has a greater thickness than that of the thin-film structure in the comparative example, and that heat conductivity of the thin-film structure **40** in a c-axis is less than half the heat conductivity of the thin-film structure in the c-axis in the comparative example.

[0137] Additionally, according to a D. Cahill's model, in a case of a thin-film structure formed of $Bi_2Te_3$, a theoretical minimum value of heat conductivity of the thin-film structure in a c-axis is about 0.14 W/(m·K), and a theoretical minimum value of heat conductivity of the thin-film structure in an a-b axis is about 0.28 W/(m·K). According to a Slack model, in a case of a thin-film structure formed of $Bi_2Te_3$, a theoretical minimum value of heat conductivity of the thin-film structure in a c-axis is about 0.28 W/(m·K), and a theoretical minimum value of heat conductivity of the thin-film structure in an a-b axis is about 0.55 W/(m·K).

[0138] In the example, even though the thin-film structure **40** is formed of a material different from $Bi_2Te_3$, it may be